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AN EVALUATION OF LIQUID AND GREASE LUBRICANTS FOR SPACECRAFT APPLICATIONS

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INTRODUCTION

Most unmanned spacecraft have systems and experiments which include mechanical parts that need to be lubricated. Such moving parts may be operated with relatively low motive power because of electrical power limitations on these solar powered spacecraft. In addition, they must perform satisfactorily with low torques over a range of temperatures and operating parameters, and they must do so after and during a broad gamut of conditions, including long term storage in air or other gas before launch and long term exposure to vacuum after launch. Because there is a variety of contractors involved in the various programs, each of which may decide on the lubrication system for their particular mechanical component, there is understandably a large variety of oils and greases being used for various reasons.(1) One of the more compelling reasons is that of past space usage — few contractors are eager to be the first with an "untried" lubricant.

For these, and other reasons, it was decided that the reliability of lubricated components for space use would be increased if the number of fluid lubricants used could be reduced to a small group that would have the attributes necessary for any unmanned spacecraft application. Before this aim could be accomplished, some evaluation of the lubricants had to be made upon which to base the selections. To make the evaluation, it was decided to look at the lubricants from two aspects that are important to spacecraft use, viz., their volatility in vacuum, and their boundary lubricating capability.

Although vapor pressure information for some liquid lubricants was available from the literature, such information was not available for all those of interest. In addition, there seemed to be some disagreement in the vapor pressure values from various sources. Because of these reasons, and because the vapor pressures and evaporation rates of oils and greases may change with time in vacuum as the lighter weight molecules evaporate, it was decided to evaluate the volatility of all of the lubricants in the same apparatus and under the same conditions. Therefore, the results can be compared to one another without the question of validity based on different sources.

Similarly, the lubricants were all evaluated for their lubricating capabilities on the same test equipment and under similar conditions, again, avoiding the question of comparability of results from other sources.

EVAPORATION TEST APPARATUS AND METHOD

The apparatus used to make the evaporation measurements (shown in Fig. 1) was somewhat like that in ASTM D2715-68T and consisted of an Ainsworth recording vacuum microbalance attached to a 3-inch diameter by 24-inch long quartz sample chamber on a vacuum system pumped down by a 6-inch diameter diffusion pump equipped with a liquid nitrogen cold trap. A multi-pen recorder provided a continuous record of temperature, pressure, and weight. The sample temperature was raised by means of radiation from a wrap-around electric resistance heater on the outside of the quartz chamber; a thermocouple hanging beside the sample monitored the temperature. A previous calibration check had been run in which a thermocouple immersed within the oil was compared with the outside one. The latter couple followed the former within 2°C.

The oil and grease samples were placed in clean glass vials (Fig. 2) that measured an average 1.054 cm (0.415 inch) I.D. at the neck by 4.445 cm (1.75 inch) high in such quantity that 2.54 cm (1 inch) of vial remained above the surface of the lubricant to control the conductance, as shown by Haehner.(2) This quantity was in the 1.5-3.5 gms range depending on the density of the lubricant. To avoid entrapment of air, grease samples were injected carefully into the vial from a large-hole hypodermic syringe. In order to verify that no air was entrained, each grease sample was subjected to a vacuum of approximately 67.6-83.1 kPa (20-25 inches Hg) at room temperature for five minutes. If air were in the sample, bubble formation or grease movement would become evident.

Sample vials were suspended from one pan of the vacuum balance within the quartz chamber on a 0.160 cm (0.063 inch) diameter wire which passed through a 0.406 cm (0.160 inch) diameter hole in a baffle plate between the balance and the chamber. The thermocouple was positioned to hang within 1.27 cm (0.5 inch) of the vial at the level of the sample. After the balance was tared, the system was pumped down to its lowest pressure at room temperature, normally in the 10^{-5} Pa (10^{-7} torr) range.

The aim of the test was to obtain the steady-state weight loss at each increasing temperature level above room in steps of 15°C until the loss rate became too great for practical use or until a temperature of 105°C was reached. The time interval at each temperature step was at least one hour, and the vacuum level maintained was always less than 6.5×10^{-4} Pa (5×10^{-6} torr), unless the sample outgassed excessively.

Steady state weight loss rates were obtained from the weight change curves and were plotted against temperature.

LUBRICATION TEST APPARATUS AND METHOD

To evaluate the lubricating capabilities of the oils and greases, the LFW-1 friction and wear test apparatus(3) was used, primarily because it was readily available. However, this tester was used also because of its versatility and current popularity, because test samples are readily obtainable, and because it is relatively simple to operate. The tester is pictured in Fig. 3 equipped with a strain-gage load cell for measuring friction force, a 30 to 1 load lever arm, and a transparent plastic chamber protecting the sample from gross contamination.

It was desired to select a set of test conditions that would somewhat simulate the limited lubrication situation of a large proportion of spacecraft gear and bearing applications and, at the same time, provide a means of comparing the boundary lubricating performance of the oils and greases. Further, it was desired to load the rotating ring and stationary block samples to a Hertzian stress value that would not be too unlike those reached in many spacecraft bearings and gears. Therefore, the following test conditions were selected:

100 rpm (11 meters (36 ft)/min. surface speed)

667 N (150 lb) load

3.79×10^5 kPa (55,000 psi) static Hertz stress at start

Continuous unidirectional rotation

Room ambient atmosphere and temperature

0.127 - 0.381 micron (5 - 15 microin.) rms surface finish

Limited lubrication

Failure criterion of 222.4 N (50 lb) friction force ($\mu = 0.33$)

1×10^6 revs. end of test.

Tests were conducted with blocks and rings made of the following steels: 52100, 440C, 303, 4620, and 01 tool. In a few tests, the surfaces of the rings and blocks were metallographically polished to a finish of less than 0.025 microns (<1 microin.) rms. All rings and blocks were tested for hardness and were in the range of 58-63 R_c, except for the 303, which was 26-29 R_c.

In preparation for the test, the rings and blocks were cleaned in several hot washes of 1:1 ethyl alcohol and chloroform, dried, weighed, and stored in individual petri dishes in desiccators. All handling of the rings and blocks after cleaning was done with clean laboratory metal tools or plastic gloves. Prior to each test, the area of the test machine in the vicinity of the samples was wiped with freon, alcohol, and chloroform; and the plastic humidity chamber (minus its front panel) was installed.

The clean and dry ring and block were then carefully installed onto the machine, and were then liberally wetted with the oil being tested by means of hypodermic syringe and were allowed to drip for 5 minutes before the machine was turned on, and the test started. In the case of the grease tests, the ring and block were liberally coated with the grease by means of a metal spatula but no set waiting time was observed. Care was taken to insure that the lubricant in each case covered the interface between the ring and block before movement between them was affected. A small thermocouple bead was inserted into the hole in the block, located approximately 2.54 mm (0.1 in.) from the wear face. The final step before the machine was turned on was the fastening of the front panel onto the plastic humidity chamber that was used to protect the samples from gross contamination.

After the 5-minute drip period, the LFW-1 machine and recorder were turned on, and the speed control quickly turned up to 100 rpm. Within the first 10 revs., a 8.9 N (2 lb) weight was placed on the bale rod, and the second 8.9 N weight was added within the next

10 revs., and the final 4.4 N weight within the next 10 revs. With the 30 to 1 ratio of the lever system, the final load on the ring and block was 667 N (150 lb), or a static Hertz stress of 3.8×10^5 kPa (55,000 psi) at the start.

The test was run for 1×10^6 revs., or until a friction force of 22.7 kg (50 lb) (μ of 0.33) was developed, at which point the machine automatically shut itself off. During the test, the friction force and the block temperature were continuously recorded, and the revs. were counted. In addition, frequent observations were made of the lubricant test sample, and notes were made on the physical characteristics of the lubricant. Following the test, the metal samples were photographed, cleaned, and weighed; the wear scar was photographed at magnification, and its width measured.

EVAPORATION TEST RESULTS

Tables I and II present information about each of the lubricants tested, and Figures 4 and 5, respectively, present the evaporation rate curves of the oils and greases that were obtained. Because of the improved lubricating performance of some oils with a tricresylphosphate (TCP) addition,(4) some oils containing it were included in the test, as well as TCP, itself. In addition, some of the oils and greases were tested as received from the manufacture and after being vacuum devolatilized, and one was tested with a lead naphthenate (LN) addition.

Although the samples were not weighed before and after the test, the amount of lubricant lost was quite small so that there did not appear to be any change in the lubricant level. In addition, the quartz chamber above the heating mantle exhibited very little lubricant condensation, except in those tests of a few oils which evaporated readily in vacuum at room temperature.

At the conclusion of each test, the vial was examined for evidence of oil creep to the exterior surface, but none was noted. Inasmuch as the evaporative loss was controlled by the cross sectional area of the vial opening and the conductance of the vial above the surface of the lubricant, no concern was made of any possible oil creep up the internal surface of the vials.

No attempt was made to ascertain if the observed evaporation rates followed the traditional Langmuir equation,(5) which is effective for liquids of one molecular weight. The object of the evaporation tests was to obtain a practical comparative evaluation of the lubricant evaporative performances. Therefore, although it is recognized that condensation of any evaporated molecules onto the wire holding the sample vial would affect the true evaporation rates, it is felt that, because all of the tests were subjected to the same conditions, such an effect would cancel out in the comparisons. Additionally, it was felt that the amount of such condensed oil should be relatively small.

In each case, the same oil and grease samples were subjected to the increasing temperature; therefore, the evaporation rates shown at the higher temperatures may be slightly lower than if a fresh sample were used at each temperature level, as required by ASTM D2715-68T. However, this effect should be quite small because the time of exposure at each temperature was relatively short (compared to actual service), having been from 1-2 hrs., and the total amount of lubricant lost was less than 10 mgms. out of a total of about 1.5 to 3.5 gms. Generally, only a single evaporation test was conducted for each oil and grease because of the time required and the need of the equipment for other purposes. In two instances, the tests were repeated because eruptions of the sample under vacuum occurred at some elevated temperature which caused a sudden loss of some of the sample. Comparisons between the data before the eruptions and the repeat tests indicated good reproducibility.

The curves are plotted on regular coordinates to more vividly show the difference among them. These curves also permit an inflection temperature to be selected in most cases at which the rate changes quite drastically, as shown in Fig. 6. Based upon these curves, a selection of the least volatile oils and greases can be made for further discrimination on the basis of other parameters, such as viscosity, pour point, or whatever. The family of curves also seem to indicate that below about 60°C, a wide variety of oils can be used in vacuum without great loss. In most spacecraft applications the bearing temperatures are kept below this temperature. Of course, at asperity contacts, microscopic flash temperatures are said to be much higher; however, if good surface finishes and good film-forming lubricants are used, there should be few such contacts.

Some of the lubricants were tested in the 'as received' condition and also after being devolatilized for 24 hrs. at 66-93°C in a vacuum of 10^{-1} to 10^{-4} Pa (10^{-3} to 10^{-6} torr). Fig. 7 presents curves showing the effect of the devolatilization in reducing the subsequent evaporation rates. Friction and wear tests that were conducted with the devolatilized samples indicated no degradation of performance.

Because pressure additives are employed in some lubricants, evaporation tests were conducted to determine their effect. Fig. 8 illustrates the effect of additions of tricresylphosphate (TCP) and lead nephthenate (LN) on the evaporation rates of oils of different volatilities. These data suggest that, when added to oils of lower volatility, the additives are the first to be lost. Therefore, in vacuum applications such differential evaporation must be taken into consideration and the additive content increased to compensate for the loss.

In the case of the grease evaporation tests, the curves may be a slight bit higher than they should be owing to air or moisture absorption. The curves in Fig. 9 depict the evaporation rates of oils M and J" and of the greases, I and H, respectively, which were made from them with inert thickeners, fine SiO_2 in the former and a powdered fluorocarbon in the latter. One would expect that the rates would be the same for both the oil and the grease.

LUBRICATION/WEAR TEST RESULTS

The lubrication/wear tests were conducted on the LFW-1 machine as they could be fit into the regular work schedule. Accordingly, there were not too many tests that were repeated, and tests with the various oils and greases were interspersed in no set fashion. As will be seen from the data, there was some scatter in performance obtained, but the data did tend to show the superiority of one lubricant over another.

In the presentation of the test results, the oils were separated into major groupings of silicone, mineral, polyether, and ester types; and these are given in Tables III, IV, V, and VI, respectively. Because the grease tests were fewer in number, their results are presented in a single table, Table VII. Besides the number of revolutions to the failure point of a μ of 0.33, the data also include the average width of the wear scar developed on the stationary rub block (as measured from 3X photographs), and the condition of the lubricant at the end of the test.

The lubricant end conditions indicated in the tables are as follows:

For oils:
A. Fluid, little debris
B. Viscous, dark
C. Dry, black

For Greases:
D. Wet, some darkening
E. Semi-wet, dark
F. Dry, black

In the tables, the letter S in the metal column refers to low alloy steel rings of 4620 and blocks of 01 tool steel. Otherwise, the rings and blocks were made of the same indicated alloy in each case. Figure 10 pictures examples of some of the types of wear scars that developed on the blocks; the ones that galled had a greater variety of scars.

In those cases where the friction force did not increase to the failure level, the test was terminated at 1×10^6 revolutions.

Although weight measurements were made of the clean rings and blocks before and after the tests, the weight change data is not presented because it did not appear to indicate any logical performance evaluation. In most cases, the weight changes were so small (a few tenths of a milligram) that they were within the balance error range.

Silicone Oil Tests — Table III

Five different silicone type oils were tested, three of which were fluorosilicones. As Table III indicates, the formerly popular space lubricant, A, is a relatively poor one for developing a hydrodynamic film; and it failed early by allowing galling to occur, which is indicated by the letter g adjacent to the wear scar dimensions. The series of tests with oil A is one of those in which a significant number of repeat tests were made to indicate the spread of results. Although this spread ranged from 2K to 27K revolutions, this level of performance is poor compared to that of the other oils. The wear scars were not very large because galling occurred between the ring and block very early in the tests. In the case of the test with the 303 stainless steel ring and block, the failure occurred even before the full 22.2 N load could be applied to the loading rod. It is known that the soft metals, such as 303, do gall easily when there is a lack of adequate lubrication.

This oil lubricant was used to conduct a few tests to indicate the effect of a pressure additive, TCP, and of surface finish. Mixture tests indicated that Oil A would accept in solution up to about 1.75 wt % of TCP. The wear tests indicated a definite improvement in lubricating performance on the low alloy steel with TCP additions of 1 - 1.75%; however, there was no improvement on the more noble steel, 440C. As stated earlier, the as-received surface finish of the rings and blocks was in the range of 0.127-0.381 micron (5-15 microin.). A few were polished metallographically to a finish of less than 0.025 micron (1.0 microin.) and tested with a reduced load (400 N - 90 lb) and with an increased load (800 N - 180 lb) from the bulk of the tests. As expected, the finer surface finish allowed the establishment of a hydrodynamic film of oil under the test conditions. The tests were terminated before the 1×10^6 rev. point because of a power outage in one case and need for the machine in another, but the improvement was well indicated.

In one case, the bulk carbides were electrolytically etched out of the polished surface of the ring, which was then vacuum impregnated with Oil A, and tested; failure occurred quickly with galling, indicating the damaging effect of micropitting on the establishment of a hydrodynamic film.

The tests with the alkylated silicone oil, B, suggest that it might be a better lubricant on the 440C steel than Oil A, but not much. The fluorinated silicone oils, on the other hand (C, D, E) definitely performed much better.

Mineral Oil Tests — Table IV

In general, the mineral oils performed better than the silicones on the bearing steels. Only one test was conducted on the 303 austenitic stainless steel that is sometimes used as gear stock, and that common spacecraft oil (F) failed by allowing galling before the full load could be applied. Other tests were conducted with that oil and two pressure additives (TCP and LN) at higher loads which seem to indicate a superiority of the TCP.

The G oils are a series of homologous mineral oils that all contain some TCP but vary in viscosity and volatility. The limited wear tests conducted with them indicate that they are all good fluid film formers, which may be the result, at least in part, of the TCP contents. However, some of these are too volatile for most space applications.

Perfluoroalkylpolyether Oil Tests — Table V

The latest lubricants of interest for spacecraft use are the synthetic fluorocarbons, the perfluoroalkylpolyethers, which are available in a range of viscosities. Table V presents the wear test data generated for three of them. Because oils J and J' exhibited high evaporation rates in the evaporation tests, not much wear testing was performed with them. Their test results, however, indicate that they are good lubricants for the bearing steels. The tests with the more viscous oil, J", reiterate the good performance of this type of oil on the bearing steels, as well as on the austenitic stainless steel (303). The single high load (1334 N - 300 lb) test, when compared with the similar tests with mineral oil, F (Table IV), suggests that it might be a better lubricant than Oil F, but not better than Oil F with the pressure additives.

For some reason, the 52100 steel blocks developed wear scars that were about twice the width as those developed on the 440C steel blocks, and the weight losses were about 10 times greater. Whether or not the difference in corrosion resistance between the two steels is involved in this performance was not investigated; however, no visual evidence was noted in the tests to suggest that a corrosion reaction was involved. It was reported in the literature(5) that the PFAPE lubricants cause or allow some corrosion on bearing steels. To verify this report from the standpoint of storage, a ring and block of both 52100 and 440C bearing steels were wetted with and partially immersed in the J" oil at room temperature for over two years. Periodic visual examinations were made of these samples, and no evidence of corrosion was noted, even after two weeks of exposure at 65°C in a humid environment.

Ester Oil Tests — Table VI

Table VI lists the wear test data for several ester-base oils and for the TCP. All of the oils except M are diesters that conform to Mil-L-6085; M is a triester. In general, the data disclose that these low-viscosity oils are not very good fluid film formers and, therefore, fail relatively early. There did not appear to be a great deal of difference in performance among them. Also disclosed by the data is the significant and consistent improvement effected on the bearing steels by additions of TCP. This improvement was not reflected in the test on the 303 steel. However, the tests conducted with 100% TCP revealed the improved performance on all four of the steels.

Grease Tests — Table VII

Table VII gives the wear test data generated for all of the greases. Again, although there is a lack of multiple tests in most instances, the results do indicate a ranking of the greases according to the revolutions to failure. It can be seen that the silicones were poor; the mineral greases, D and F, were better on the bearing steels; the PFAPE greases, H and H', also were good on the bearing steels, as were the ester greases. None of the greases were very good on the 303 stainless steel. The indicated improvement in grease A with increased additions of TCP, coupled with the good performance of 100% TCP in the tests of Table VI, suggested that a grease of TCP and fine SiO_2 (8 wt %) might perform well. Such a grease was compounded and tested on the S steel, and ran for 828K revolutions to failure.

SUMMARY OF RESULTS

The primary purpose of this work was to try to evaluate oil and grease lubricants for spacecraft applications based upon two criteria: volatility in vacuum and fluid film formation (wear surface separation). The volatility curves that were generated with increasing temperature can serve to select those lubricants which have the lowest volatility for the maximum temperature of service in vacuum. They also can indicate those lubricants which, perhaps, should not be used at all, even in a hermetically-sealed device, because the volatility at room temperature is excessive and such lubricants would tend to be boiled out of operating bearings. The curves also display the beneficial influence of a devolatilization procedure, and the effect of pressure additive additions on the volatility of oils that are more and less volatile than the addition.

A lubrication/wear test was designed, employing available test equipment, which more closely simulates the limited lubrication conditions of most spacecraft applications than other tests. These tests pointed out that the mineral and perfluoroalkylpolyether lubricants were the best for use on the common ball bearing steels, 52100 and 440C, and that the TCP pressure additive can greatly enhance the performance of some of the lubricant types. The tests also illustrated the importance of fine surface finishes in establishing a hydrodynamic film and minimizing friction and wear; they also emphasized the difficulty in lubricating the soft (austenitic) stainless steels. Figure 11 summarizes the range of life performances of the oils and greases on the common bearing steels which illustrates the above-mentioned features.

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This report is dedicated to W. G. Grenier, recently deceased, who conducted the bulk of the wear tests and measurements.

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Table I

Oils Tested

Code	Common Name	Type	Density (g/ml)	Viscosity (cs @°C)
A	Versilube F50	Methylchlorophenylsilicone	1.05	52/38
B	SF 1147	Methylalkylpolysiloxane	0.89	49/25
C	FS 1265	Fluorosilicone	1.25	300/25
D	F6-1101	Fluorosilicone	1.27	780/25
E	Rotron	Fluorosilicone	NA	~80/25
F	Apiezon C	Mineral	0.87	90/38
G	SRG 30	Mineral	0.87	<27/38
G'	SRG 40	Mineral	0.87	27/38
G"	KG 80	Mineral	0.88	164/38
H	Teresso V79	Mineral	0.88	152/38
I	Sunvis 747	Mineral	~0.90	45/38
J	Krytox 143AZ	Perfluoroalkylpolyether	1.86	18/38
J'	Krytox 143AA	Perfluoroalkylpolyether	1.88	36/38
J"	Krytox 143AB	Perfluoroalkylpolyether	1.90	85/38
K	L245-X	Diester	~0.90	20/25
L	P-10	Diester	~0.90	15/38
M	NPT-4	Neopentyl triester	0.95	20/38
N	L401-D	Diester	0.91	13/38
O	DOA	Dioctyl Adipate	0.93	12/25

Table II

Greases Tested

Code	Common Name	Type	Channelling	Filler
A_g	G-300	Methylchlorophenylsilicone	No	Lithium
B_g	G-322L	Methylalkylpolysiloxane	No	Lithium
C_g	FS-1281	Fluorosilicone	No	SiO_2
D_g	Apiezon M	Mineral	No	None
E_g	Apiezon 10^{-9}	Fluorocarbon	No	Naphthenate
F_g	Andok-C	Mineral	Yes	Sodium
G_g	Mobil 28	Synthetic HC	No	Clay
H_g	Krytox 240AB	Perfluoroalkylpolyether	No	Fluorocarbon
I_g	KK949	Ester	No	SiO_2
J_g	Beacon 325	Ester	No	Lithium
K_g	Aeroshell 17	Ester	No	Microgel

Table III

Silicone Oil Wear Test Data

Oil	Normal Load (N/lbs)	Metal	Revs(K)	Scar Width (mm)	End Oil Cond.
A	667/150	S	2.9	.76	A
A+0.5% TCP[1]	"	S	21.4	1.02	B
A+1.0% TCP	"	S	>625	1.27	A
A+1.0% TCP+DV[2]	"	S	>986	1.02	A
A+1.5% TCP	"	S	>750	1.27	A
A+1.75% TCP	"	S	>554	1.27	A
A	"	440C	27.3	1.52g	C
A	"	440C	15.4	1.52	A
A	"	440C	7.1	1.02g	A
A	"	440C	10.4	1.52g	B
A	"	440C	22.9	1.27g	B
A	"	440C	3.3	1.02g	B
A	"	440C	2.1	1.52g	B
A Flooded[3]	"	440C	7.1	1.27g	B
A	"	303	<0.1	5.08g	A
A	400/90	440C	9.9	1.27g	C
A Polished[4]	"	440C	>853	1.27	A
A Polished & Etched[5]	800/180	440C	2.8	0.76g	C
A Polished	"	440C	>420	1.02	A
B	667/150	440C	457.2	2.79g	C
B-DV	"	440C	30.6	1.02g	A
B	"	440C	5.3	0.76g	A
B	"	440C	30.8	1.52g	A
C	"	S	234.6	1.27	B
C	"	440C	>1x10^3	0.76	A
D	"	S	266.7	1.52	C
E	"	S	>1x10^3	1.78	A
E	"	440C	>1x10^3	0.76	A

1. %TCP = wt % tricresylphosphate.
2. DV = devolatilized 24 hrs. at 65°C, 6.5 x 10^{-4} Pa.
3. Oil was added during the test.
4. Ring and block metallographically polished.
5. Carbides electrolytically etched out following the polish.

Table IV

Mineral Oil Wear Test Data

Oil	Normal Load (N/lbs)	Metal	Revs(K)	Scar Width (mm)	End Oil Cond.
F	667/150	S	>700	1.02	C
F	"	440C	> $1x10^3$	1.52	B
F	"	303	<0.1	0.76g	A
F	"	52100	> $1x10^3$	2.29	B
F	1334/300	440C	22.7	1.78	C
F+5% TCP	"	440C	317.1	2.03	B
F+5% LN	"	440C	62.1	2.03	B
F+5% TCP	667/150	52100	753.8	2.54	C
G	"	S	527.9	2.03	B
G'	"	440C	> $1x10^3$	2.03	A
G"	"	440C	>100	0.76	A
H	"	440C	721.7	1.52g	B
H	"	440C	> $1x10^3$	1.02	A
I	"	440C	> $1x10^3$	2.29	C

Table V

PFAPE* Oil Wear Test Data

Oil	Normal Load (N/lbs)	Metal	Revs(K)	Scar Width (mm)	End Oil Cond.
J	667/150	S	134	2.03	C
J'	"	S	>600	1.78	A
J	"	440C	>100	1.27	A
J"	"	S	>750	2.79	B
J"	"	440C	> $1x10^3$	1.78	A
J"	1334/300	440C	46.3	1.52	A
J"	667/150	440C	>100	1.02	A
J"	"	303	> $1x10^3$	1.78	A
J"	"	52100	670.9	3.81	A
J"	"	440C	117.8	1.02	A
J"	"	52100	> $1x10^3$	3.56	B
J"	"	52100	976.4	3.56	B

*Perfluoroalkylpolyether

Table VI

Ester Oil Wear Test Data

Oil	Normal Load (N/lbs)	Metal	Revs(K)	Scar Width (mm)	End Oil Cond.
K	667/150	S	10.9	1.27	B
K+2% TCP	"	S	$>1x10^3$	1.27	B
K+2% TCP	"	52100	>673	1.52	B
K+2% TCP	"	52100	>511	1.27	A
K	"	440C	2.1	0.76g	A
L	"	S	86.5	1.52	C
L-DV[1]	"	S	153	3.30	C
L+5% TCP	"	440C	$>1x10^3$	1.27	B
L	"	303	3.2	3.05g	C
L+5% TCP	"	303	3.0	2.54g	C
L - old stock[2]	"	440C	2.7	0.76g	A
L - new stock[3]	"	440C	4.9	1.02g	A
L+5% TCP - old stock[4]	"	440C	$>1x10^3$	1.27	A
L + 5% TCP	"	52100	$>1x10^3$	1.27	B
L	"	52100	35.2	2.29	C
L	"	52100	21.7	1.78	C
M	"	S	28.8	1.52	C
M + 5% TCP	"	S	>870	0.76	A
M + 5% TCP	"	440C	>140	2.79	C
M	"	440C	296.3	2.79	C
M + 5% TCP	"	440C	45.5	2.79	B
M + 10% TCP	"	440C	$>1x10^3$	1.52	A
N	"	440C	29.3	1.52g	C
TCP	"	S	$>1x10^3$	0.76	A
TCP	"	440C	$>1x10^3$	2.03	B
TCP	"	52100	$>1x10^3$	2.03	B
TCP	"	303	855.3	2.03g	B
TCP	"	303	$>1x10^3$	2.03	B

1. Devolatilized 24 hrs. at 65°C at 10^{-4} Pa vacuum.
2. At least 4 yrs. old unsealed.
3. Less than 6 months old.
4. Ring and block immersed 10 months in the oil-TCP in air.

Table VII

Grease Wear Test Data

Grease	Normal Load (N/lbs)	Metal	Revs(K)	Scar Width (mm)	End Grease Cond.
A_g	667/150	S	0.4	1.02	D
A_g	"	S	0.4	1.02	D
A_g+2.5% TCP	"	S	0.6	0.76	D
A_g+10% TCP	"	S	2.8	1.52	D
A_g+25% TCP	"	S	15.5	1.27	D
A_g	"	440C	0.8	1.02	D
A_g	"	303	< 0.1	3.56g	D
B_g	"	440C	22.0	2.29g	E
B_g	"	440C	110.5	3.05g	F
C_g	"	440C	0.6	0.51	D
D_g	"	440C	$>1x10^3$	1.02	D
D_g	"	303	1.4	1.02g	D
D_g	"	52100	$>1x10^3$	1.78	F
E_g	"	440C	73.2	0.76	E
F_g	"	S	106.4	1.78	D
F_g+Moisture[1]	"	S	71.2	1.27	E
F_g+Isopar E[2]	"	S	56.6	1.27	E
F_g+Toluene[2]	"	S	68.4	1.27	E
F_g	"	440C	40.8	1.27g	D
F_g	"	52100	22.8	2.03	E
F_g	"	303	7.5	3.05g	E
G_g	"	440C	$>1x10^3$	2.29	E
G_g	"	303	<0.1	3.81g	D
H_g	"	S	98.0	2.03	D
H_g	"	440C	$>1x10^3$	1.27	D
H_g	"	303	47.7	4.32g	D
H'_g+Freon[2]	"	440C	383.3	2.29	D
H'_g+Freon[2]	"	440C	264.1	1.78g	D
H'_g	"	440C	664.4	1.78	D
H'_g	"	440C	237.1	1.52g	D
I_g	"	440C	450.5	1.52g	E
J_g	"	S	627.0	1.52	F
J_g	"	440C	643.1	3.30	F
J_g	"	303	0.2	0.51g	D
K_g	"	440C	598.5	1.52g	F

1. Grease was exposed to 95% R.H. for 24 hrs. before being tested.
2. Greases were blended with the solvent in a 1:10 ratio as in grease plating, then the solvent was evaporated before being tested.

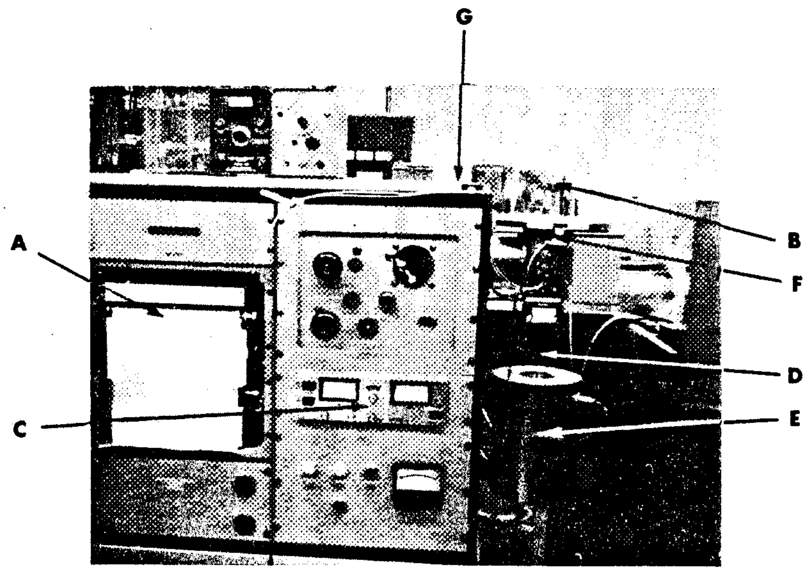


Figure 1

Diffusion-pumped vacuum system with balance and heater used to conduct evaporation tests. A. Recording chart for weight, vacuum, and temperature. B. Electronic vacuum balance. C. Vacuum controls. D. Quartz tube. E. Mantle heater. F. Baffle plate. G. LN_2 cold trap in rear of panel.

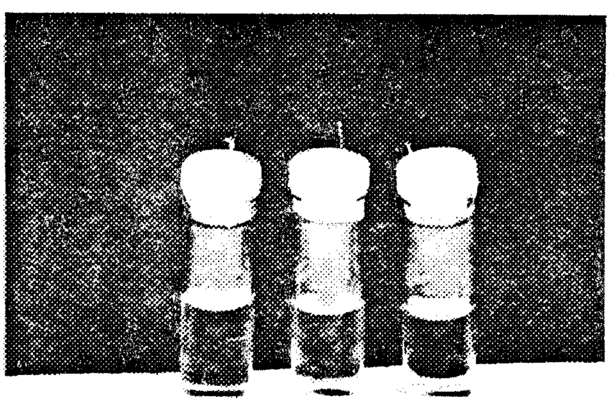


Figure 2

Samples of oil in glass vials used for the evaporation tests.

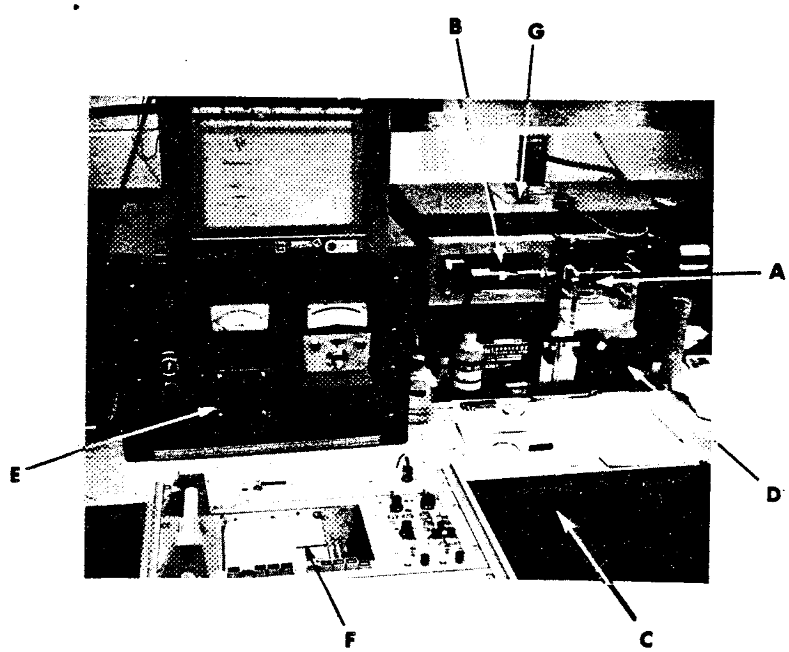


Figure 3

Dow Corning LFW-1 Friction and Wear Test Machine. A. Rotating ring and stationary block samples in protective plastic box cover. B. Friction load transducer. C. Dead weight load. D. 30:1 load lever system. E. Speed controller. F. Friction force and block temperature recorder. G. Revolution counter.

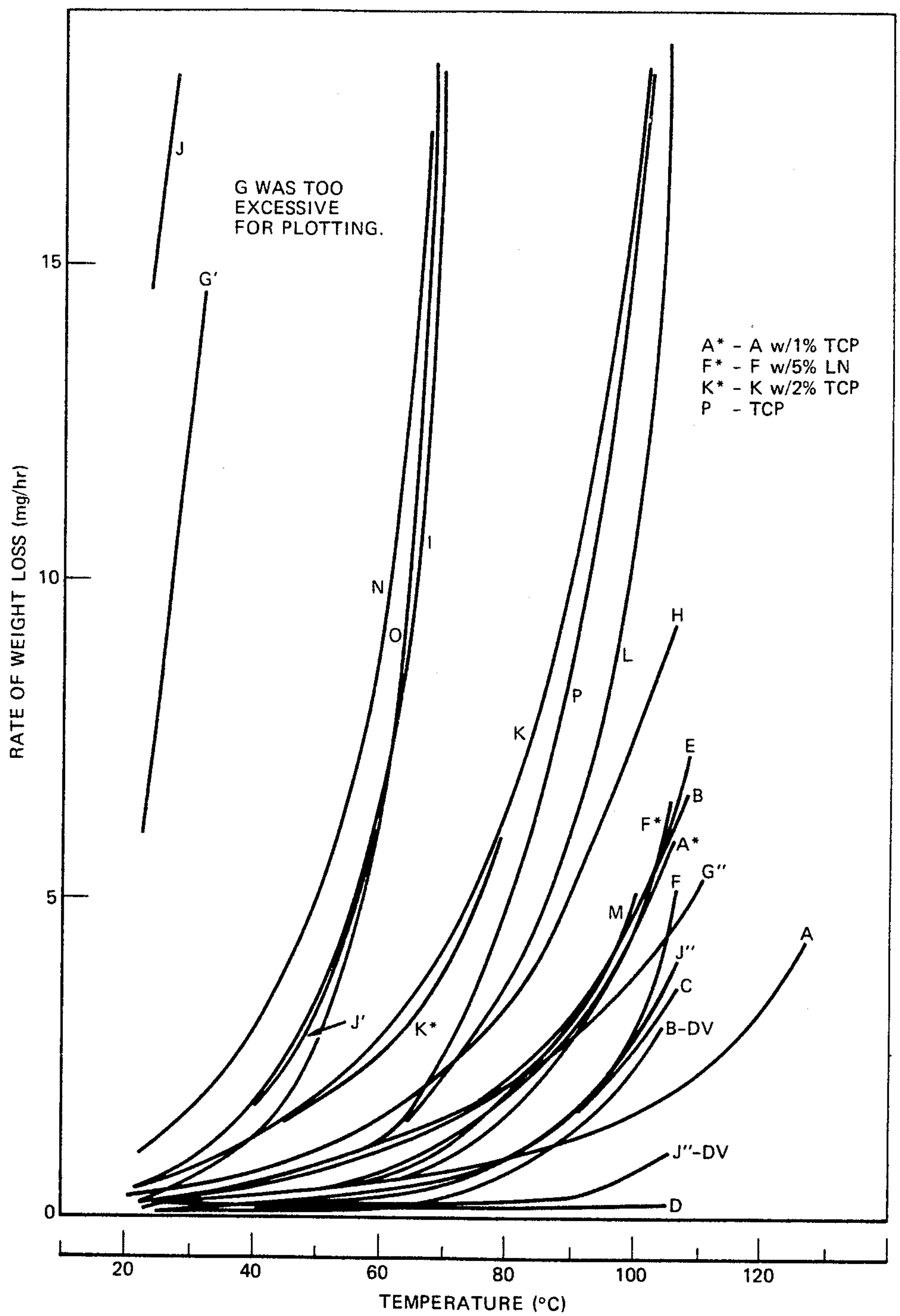


Figure 4

Evaporation rate curves of the oils on regular coordinates.

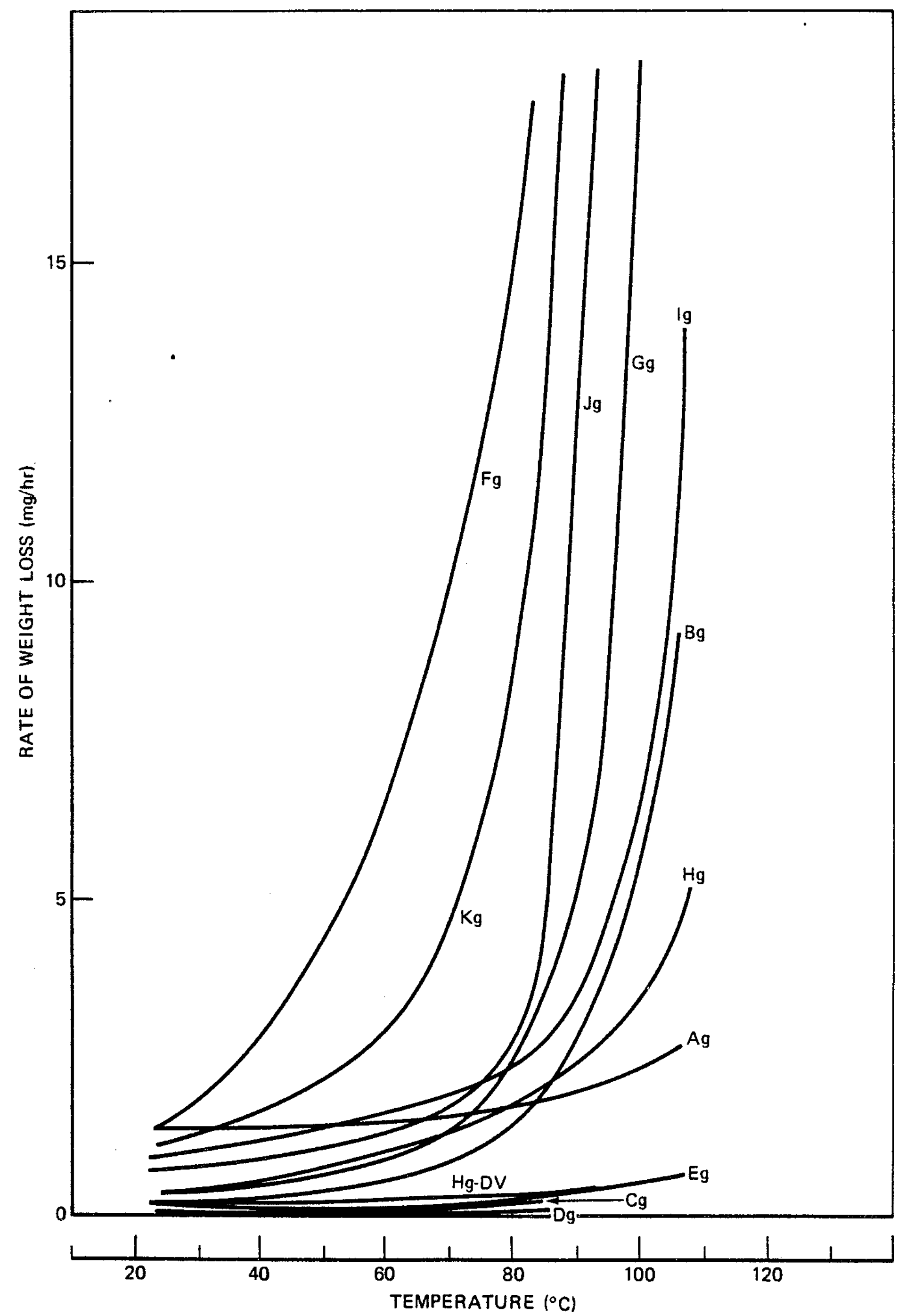


Figure 5

Evaporation rate curves of the greases on regular coordinates.

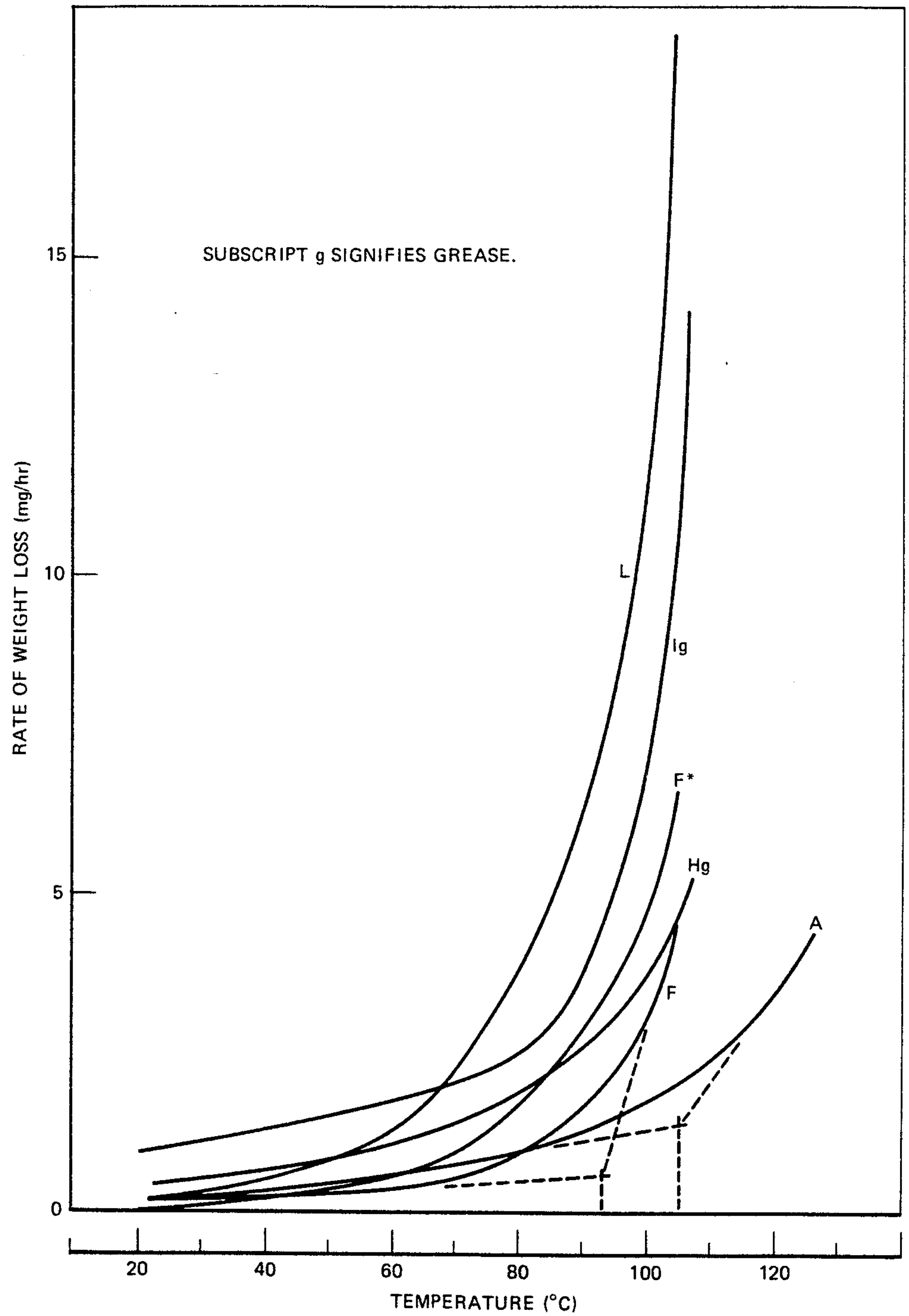


Figure 6

Some evaporation rate curves selected to illustrate the rate inflection.

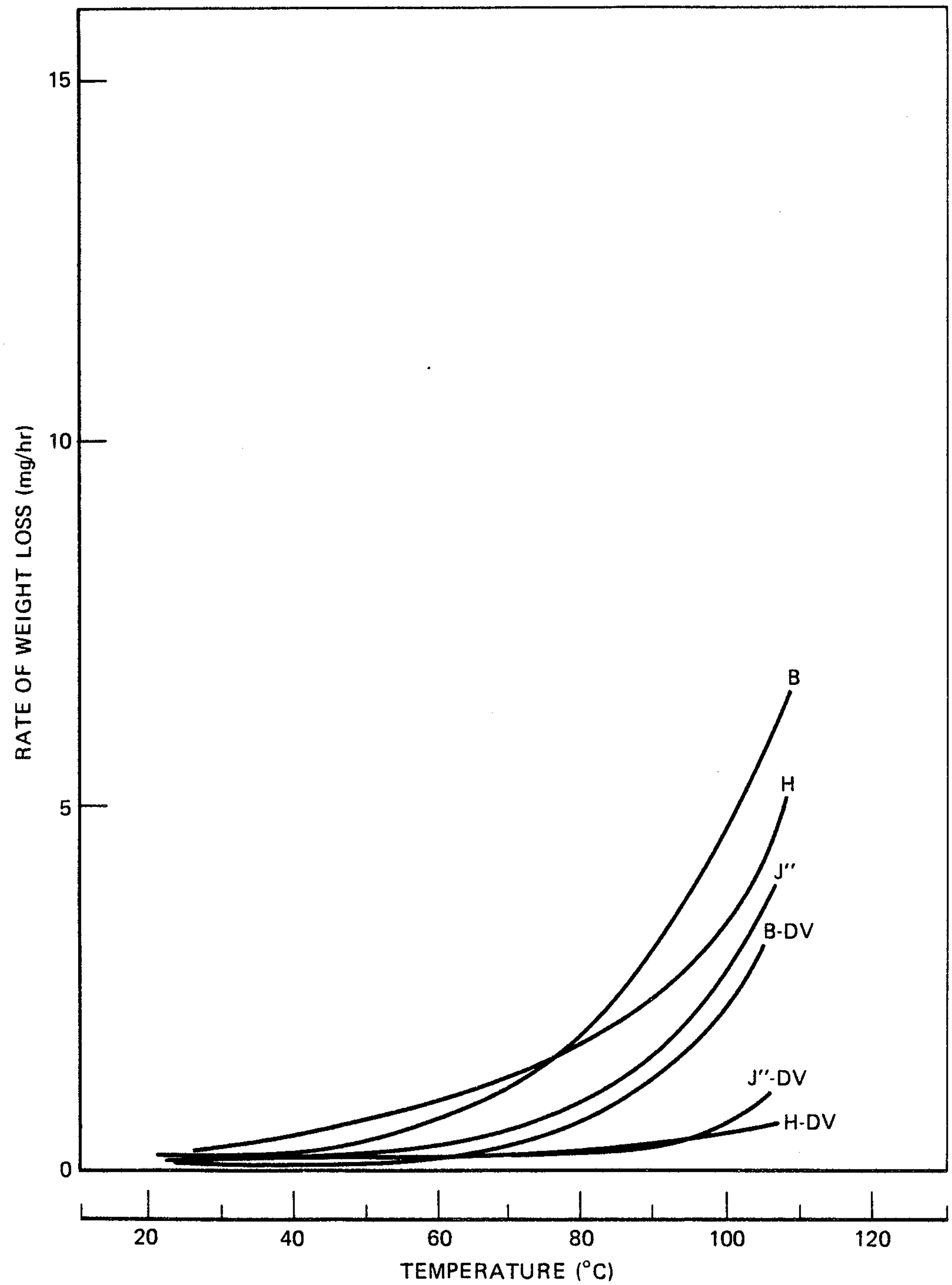


Figure 7

Some evaporation rate curves selected to illustrate the effect of devolatilization.

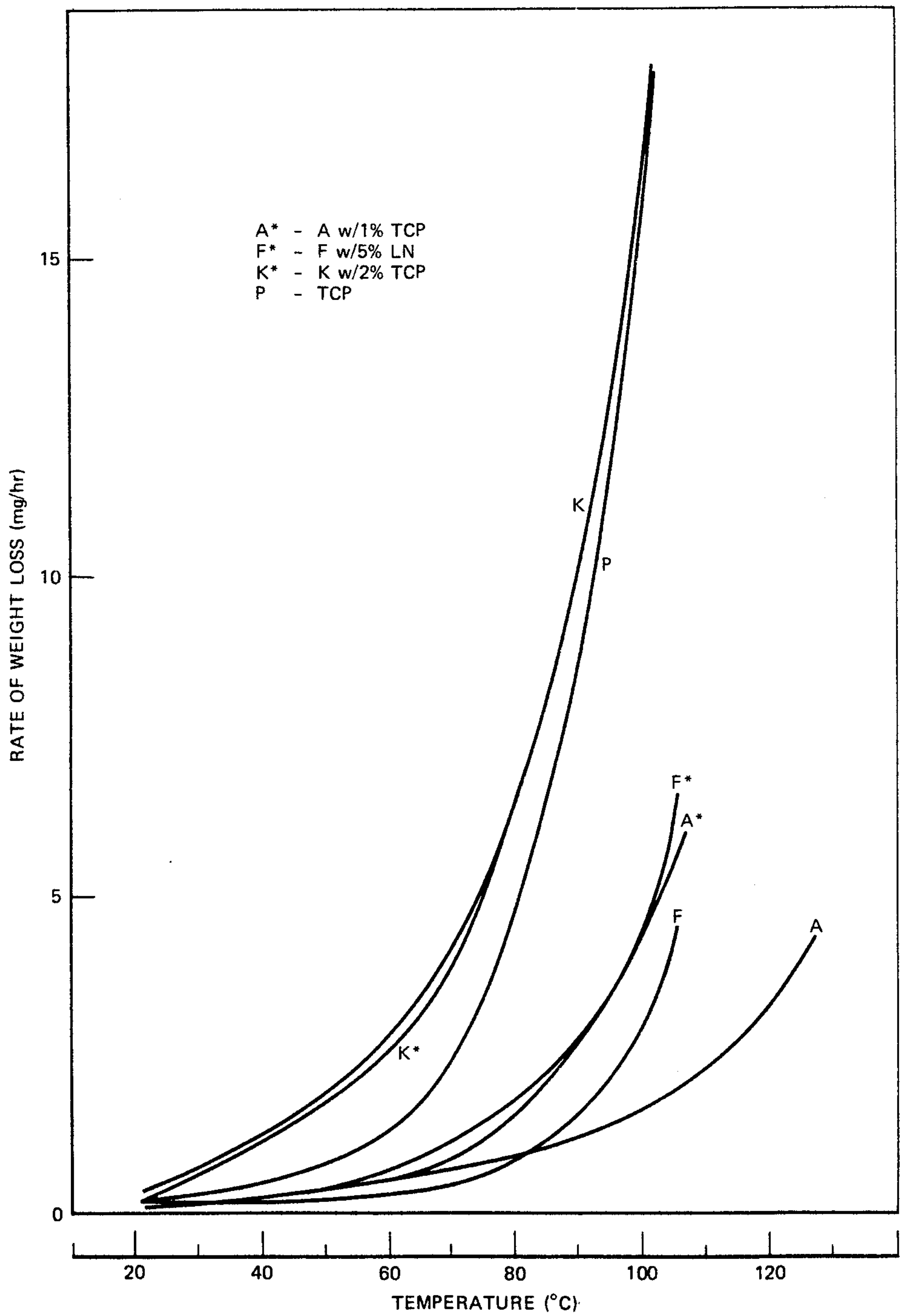


Figure 8

Some evaporation rate curves selected to illustrate the effect of pressure additives.

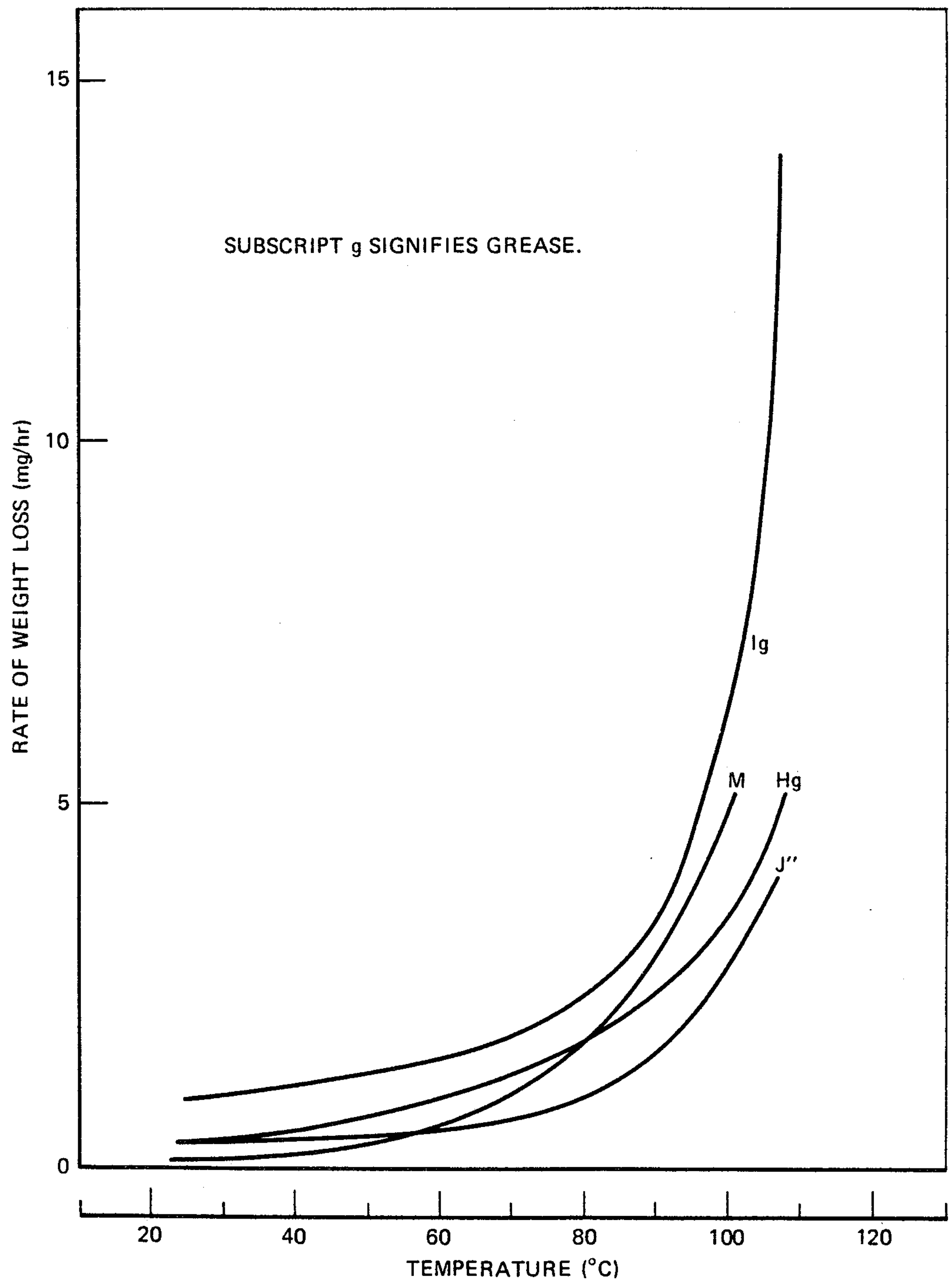
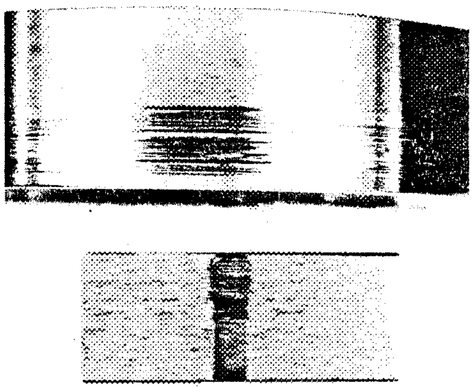
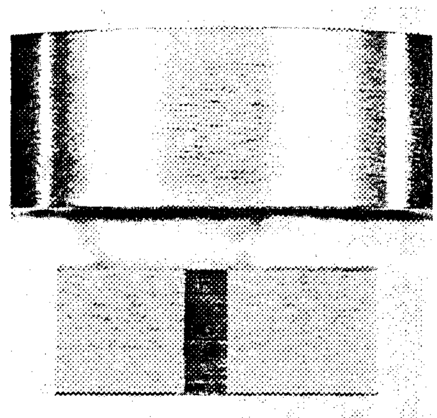


Figure 9

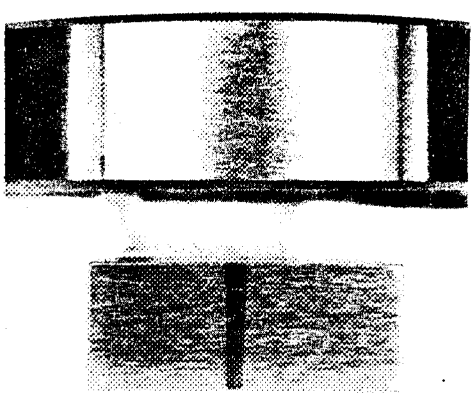
Some evaporation rate curves of oils and their greases to illustrate the differences.



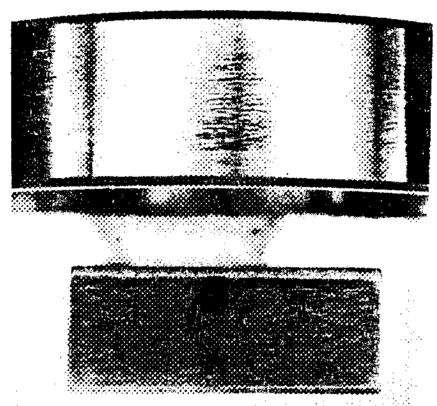
Oil B, 440C block, 30.8K revs.
Example of galling.



Oil L, 52100 block, 35.2K revs.
Large wear scar.



Grease D, 440C block, $>10^6$ revs.
Small Scar.



Oil L + 5% TCP, 440C block, $>10^6$ revs.
Film in center of scar.

Figure 10

Examples of some of the wear scars that developed on the stationary blocks.

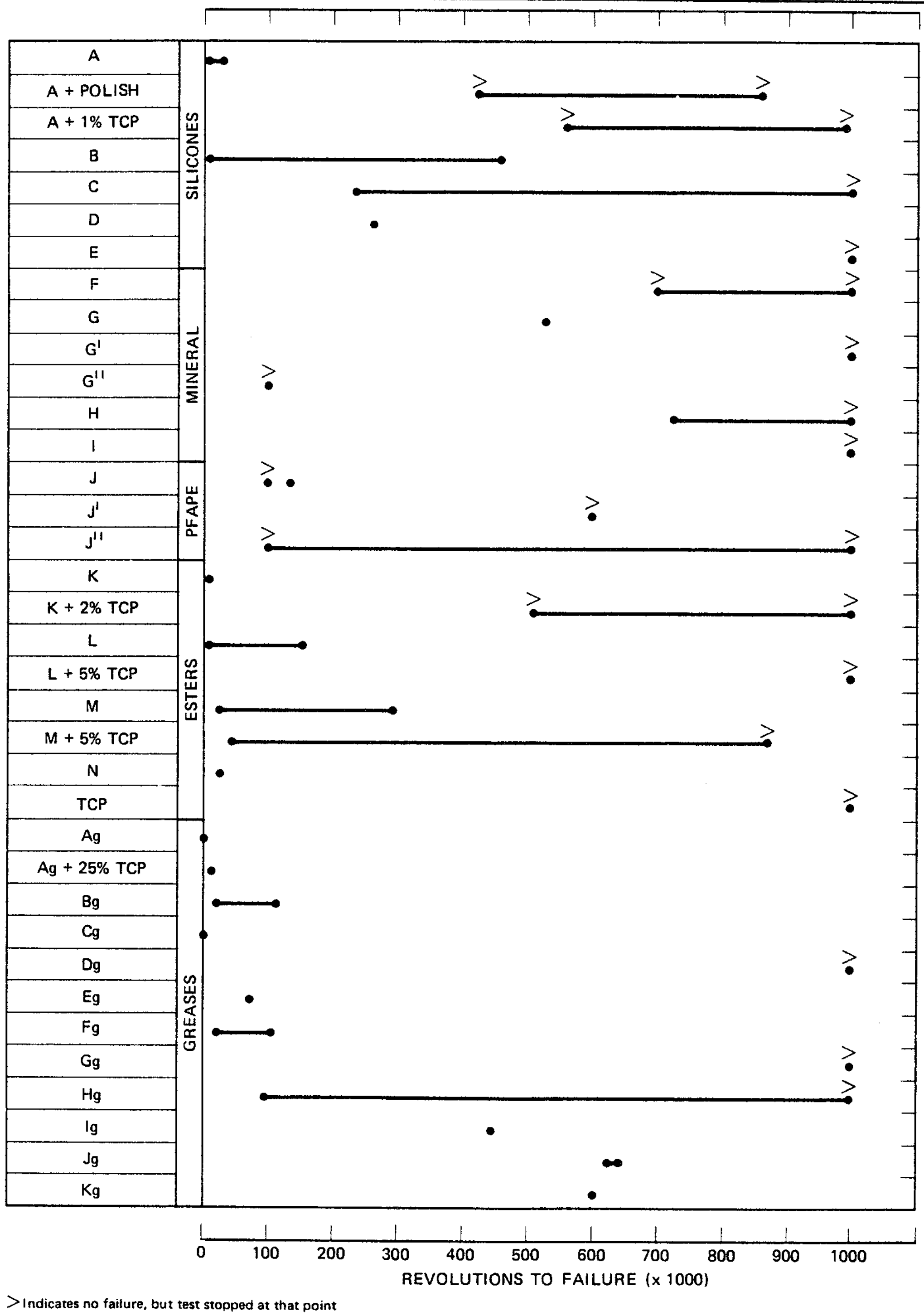


Figure 11

Summary of wear test performance of oils and greases.